Criteria Approach to Separation Assurance

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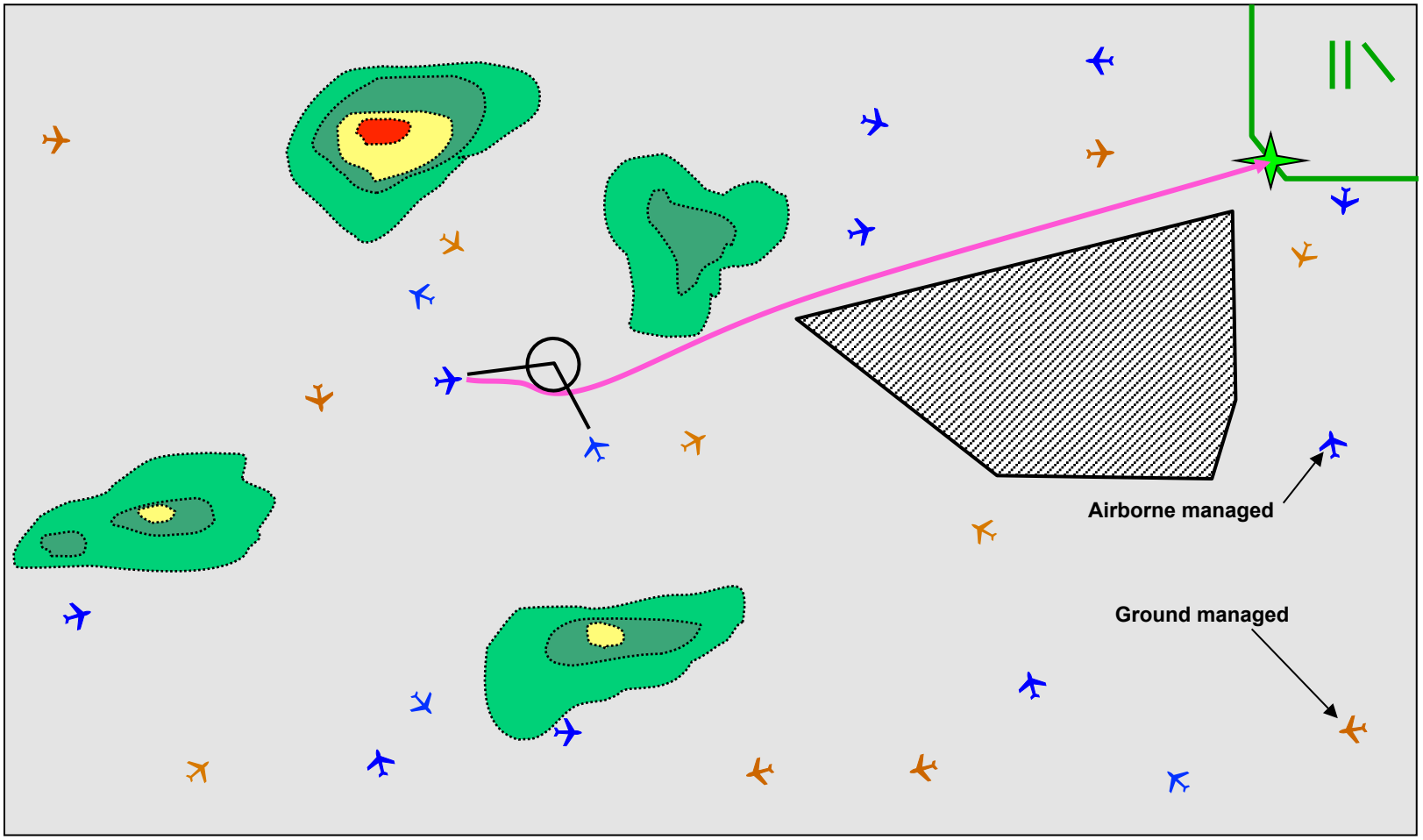
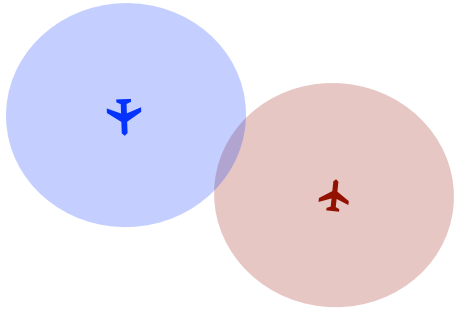
Self Separation Concept



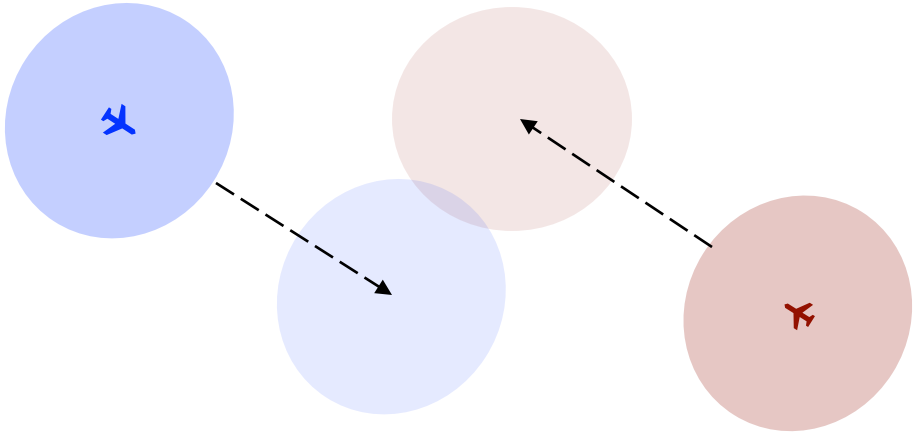
Separation and Automation

- Collision
  - Scrape paint
  - Avoid through pilot, controller, and TCAS

- Loss of Separation
  - Separation standards are violated (5nmi, 1000ft)
  - Avoid through human and/or automation decisions



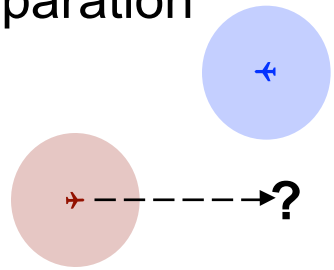
- Conflict
  - Predicted loss of separation



Separation Algorithms

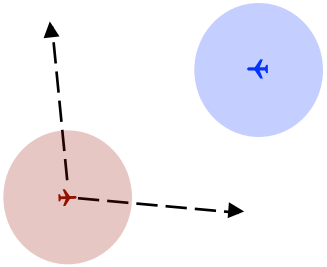
Conflict Detection

- Detect future loss of separation



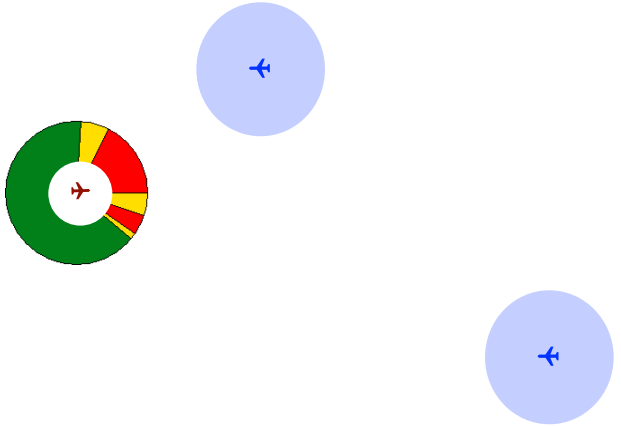
Conflict Resolution

- Suggest maneuvers to avoid a conflict



Conflict Prevention

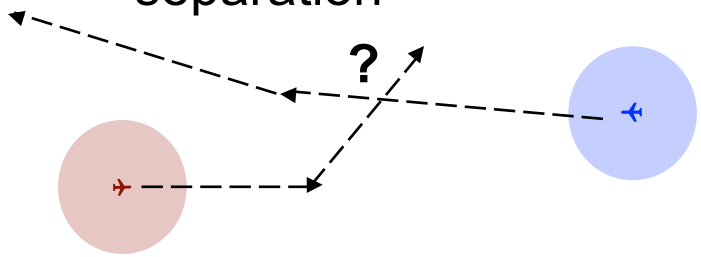
- Provide conflict-free maneuvers



Trajectory Algorithms

Conflict Detection

- Detect future loss of separation



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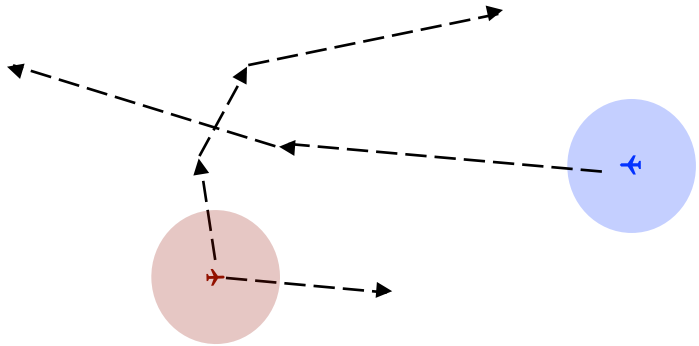

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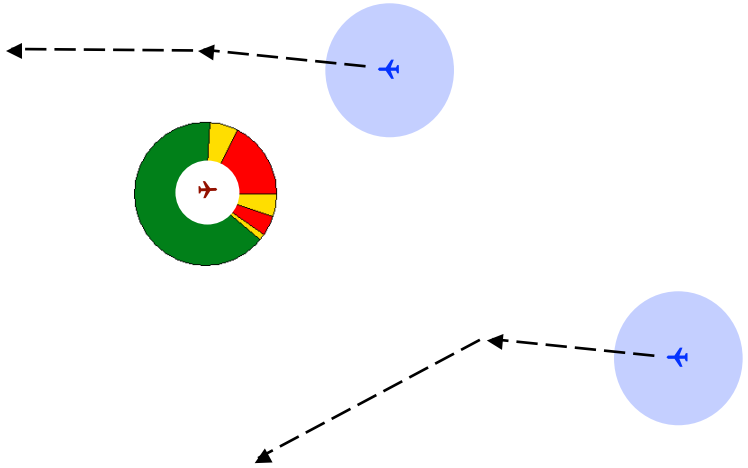
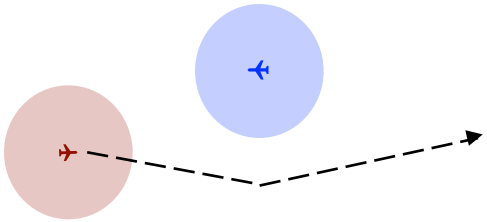


Recovery Algorithms

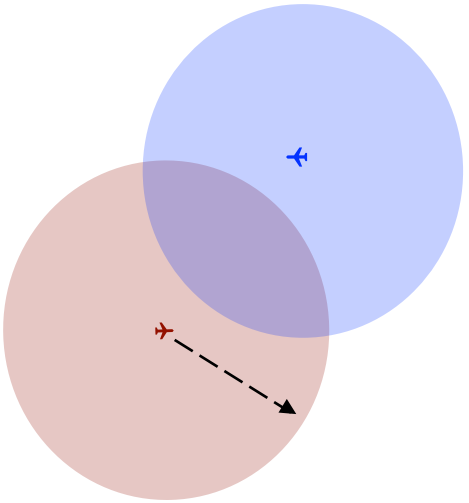
Conflict Recovery

- Suggest maneuvers to regain desired path



Loss of Separation Recovery

- For a variety of reasons separation may be lost
- Suggest a maneuver to regain separation



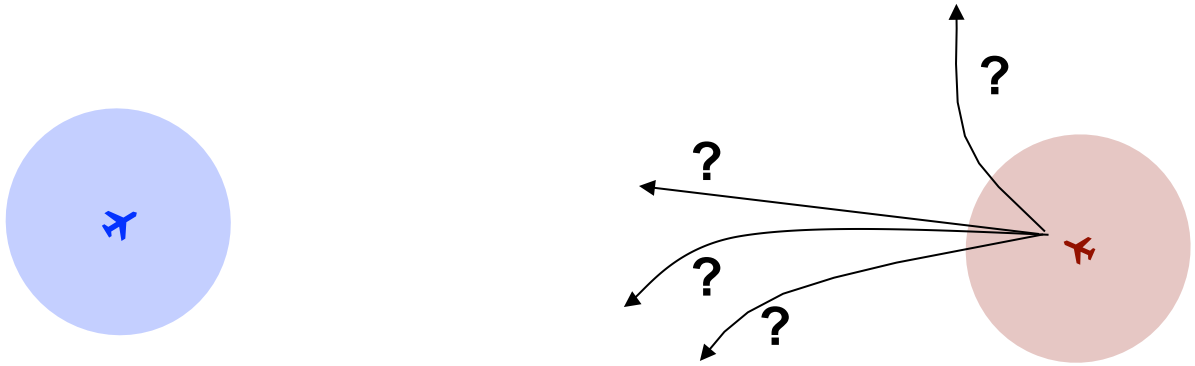
Research Goal

Develop a mathematical framework for the verification that such algorithms are correct (i.e., maintain safety properties)

Outline

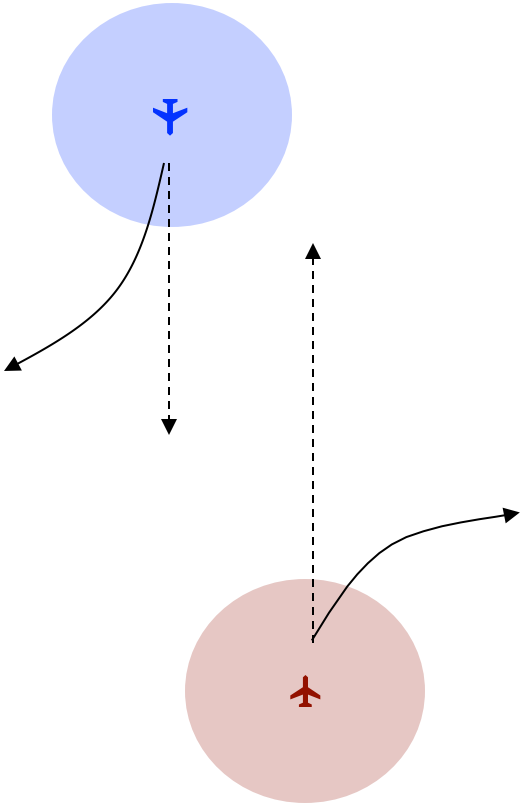
- Introduction
- Example: Resolution
- Criteria Approach to Coordination
- Using Criteria
- Criteria Details
- Summary

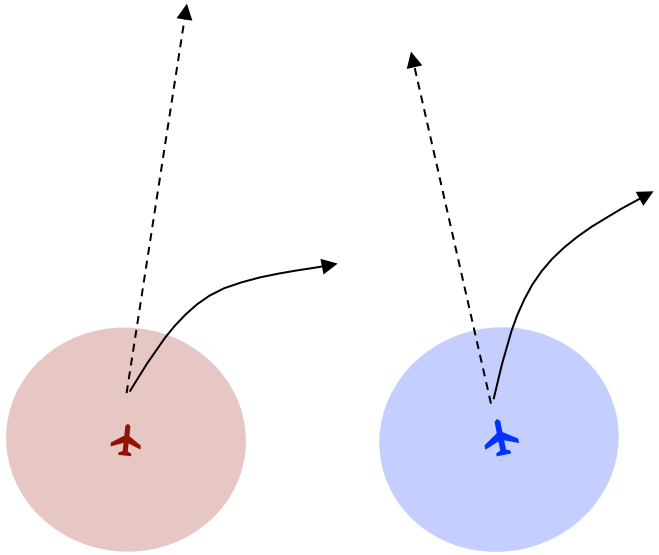
Resolution



- Each aircraft determines its own set of maneuvers to avoid the other aircraft
  - Go right/left
  - Speed up/slow down
  - Go up/down
- Safety Properties
  - Independence: free of conflicts if one aircraft maneuvers
  - Coordination: free of conflicts if both aircraft maneuver
- Customer Desires
  - No specific communication between aircraft
  - No unfair rules: lower aircraft ID goes first, etc.

Coordination Examples





Uh, oh…

Coordination

- Correctness
  - When both aircraft maneuver, is the combined maneuver safe?
  - Relies on “knowing” what the other aircraft is going to do
- How to achieve this knowledge?
  - Single algorithm
  - Multiple algorithms

Single Algorithm

- Single algorithm needs a single verification that the algorithm is coordinated with itself
  - For example, TCAS
- But this algorithm must
  - Accommodate aircraft with widely different performance envelopes
  - Have the entire fleet upgraded at one time
    - When new versions come out
  - Be used by everyone…
    - Competing airlines
    - Military traffic
    - International traffic

Multiple Algorithms

- Avoid the difficulties with a single algorithm
  - Multiple versions of TCAS are an example
- But multiple algorithms require
  - Each algorithm to be verified with every other algorithm
    - Costly NxN verification
  - This cost grows as new algorithms are added
    - and possibly exclude correct new algorithms

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We have developed an approach that allows multiple algorithms with a verification cost close to a single algorithm

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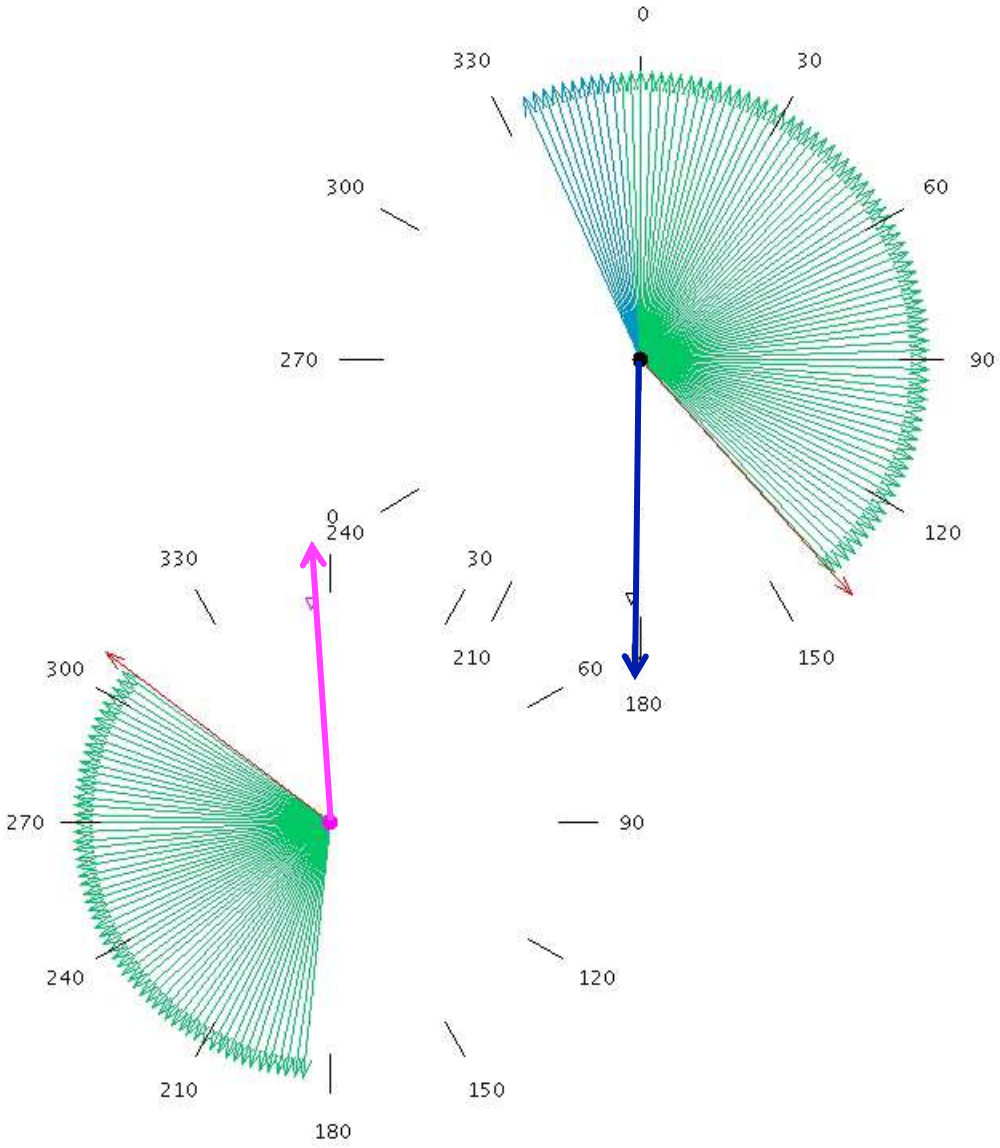
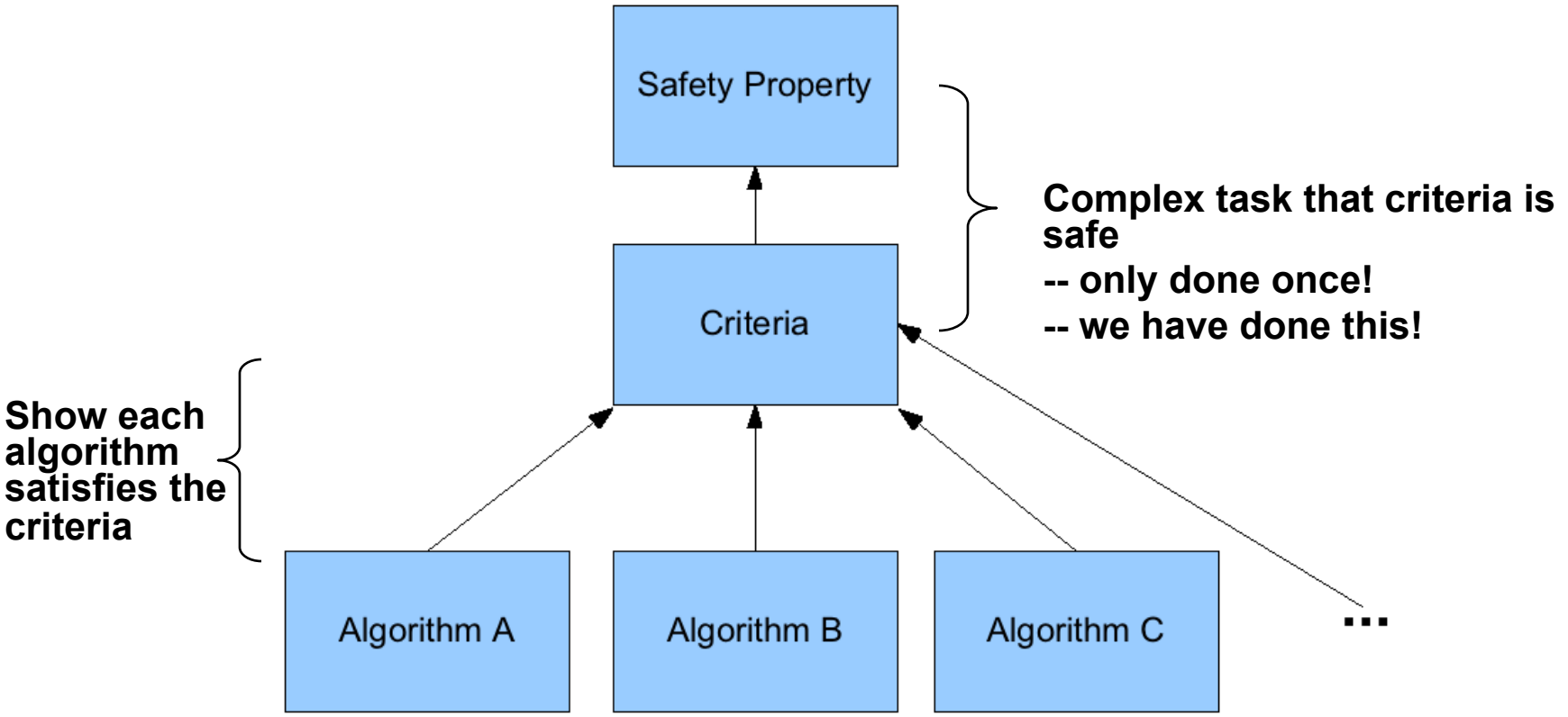
What is Criteria?



- Criteria is a range of resolutions
  - Each aircraft chooses any resolution within the criteria
  - The joint maneuver is coordinated
- Criteria is simple so algorithms can be checked in a straight-forward way

Multiple Algorithms



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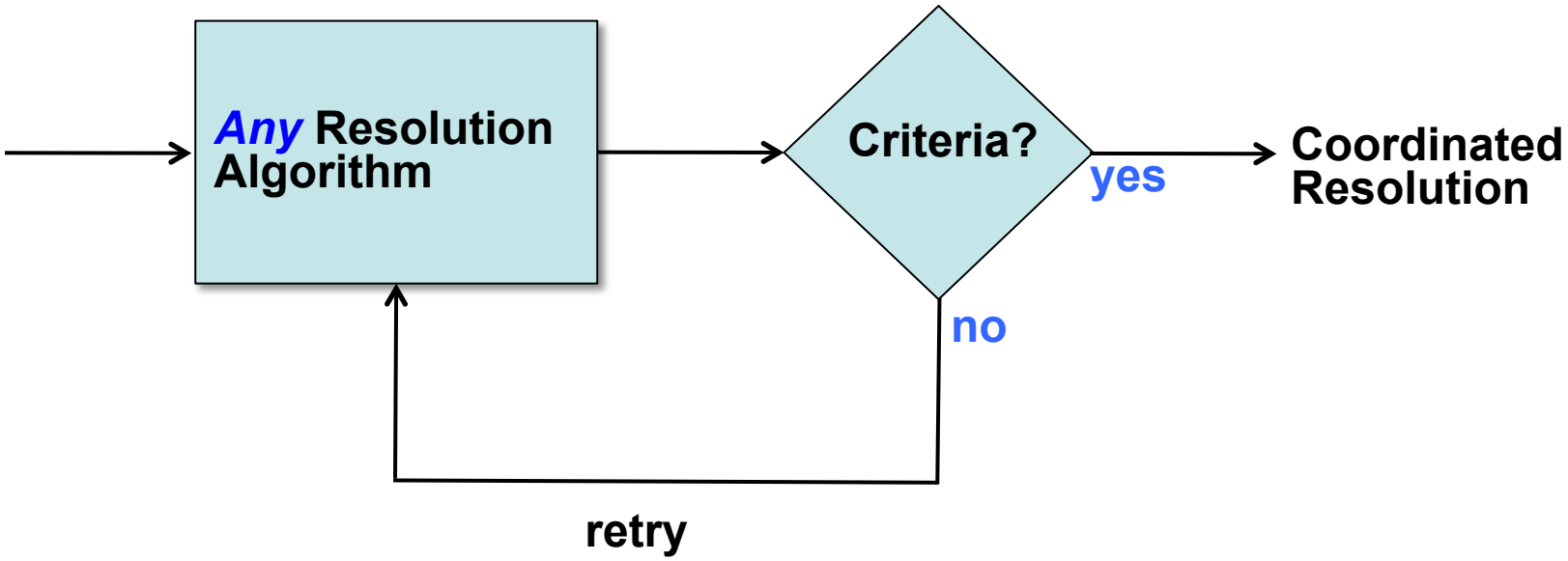
Criteria “Filtering”



Theunissen and Uijt de Haag, “Towards a seamless integration of awareness support and alerting systems: Why and how” 30th Digital Avionics Systems Conference (DASC), 2011

Integrated Criteria

- Alternately, one can check if an algorithm inherently satisfies the criteria
  - Perform a mathematical/software verification that resolutions always satisfy the criteria
  - We have done this for several algorithms
    - Anthony Narkawicz and César Muñoz. State-Based Implicit Coordination and Applications, NASA TP-2011-217067, March 2011.

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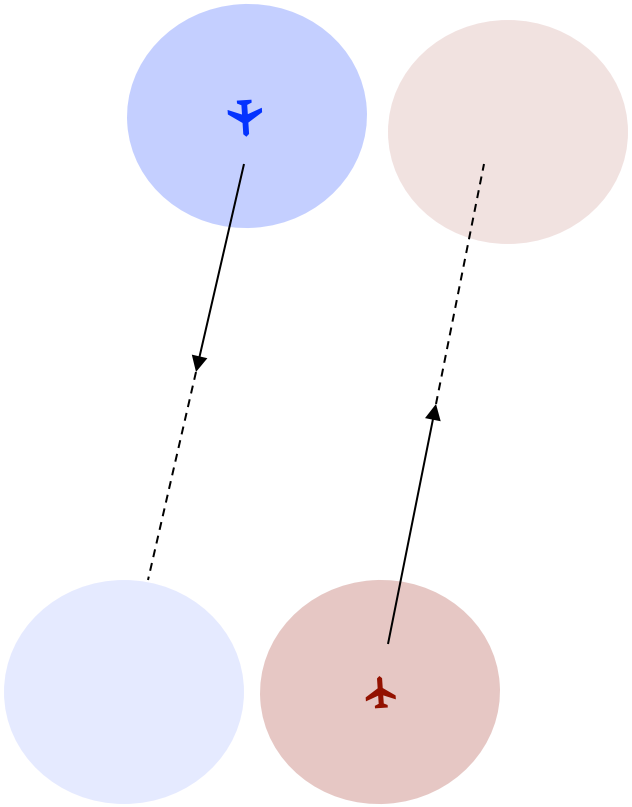
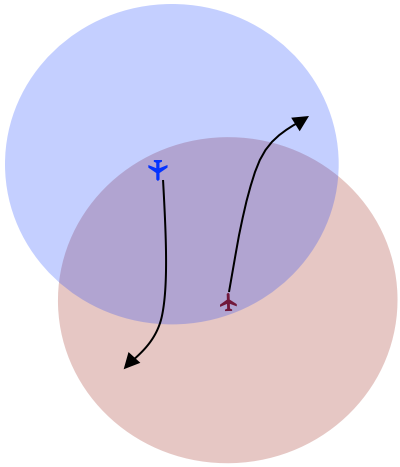
What is Safe?



Conflict-free

For all $t \geq 0 : ||\mathbf{s} + t\mathbf{v}|| \geq D$



In Loss of Separation

$||\mathbf{s} + \tau\mathbf{v}'|| > ||\mathbf{s} + \tau\mathbf{v}||$, where τ is the time of closest approach

Criteria

	in Conflict	in Loss of Separation
horizontal	$(\mathbf{s} \cdot \mathbf{v}') \geq \epsilon R(\mathbf{s}^{\perp} \cdot \mathbf{v}')$	$(\mathbf{s} \cdot \mathbf{v}') > \mathbf{s} \cdot \mathbf{v}$ AND $(\mathbf{s} \cdot \mathbf{v}') \geq ||\mathbf{s}|| \frac{(D - ||\mathbf{s}||)}{T_h}$
vertical	$\Delta > 0$ AND $t > 0$ AND $\delta = 1$ AND $s_z v_z \geq 0$ OR $\lvert s_z + t v_z \rvert \geq H$ AND $\delta \lvert s_z + t v_z \rvert v_z \leq 0$	$v_z' \neq 0$ AND $s_z v_z' \geq 0$ AND $s_z v_z \geq 0$ IMPLIES IF $v_z = 0$ THEN $\text{break\_sym}(\mathbf{s})(v_z') > 0$ ELSE $sign(v_z) v_z' \geq 0$

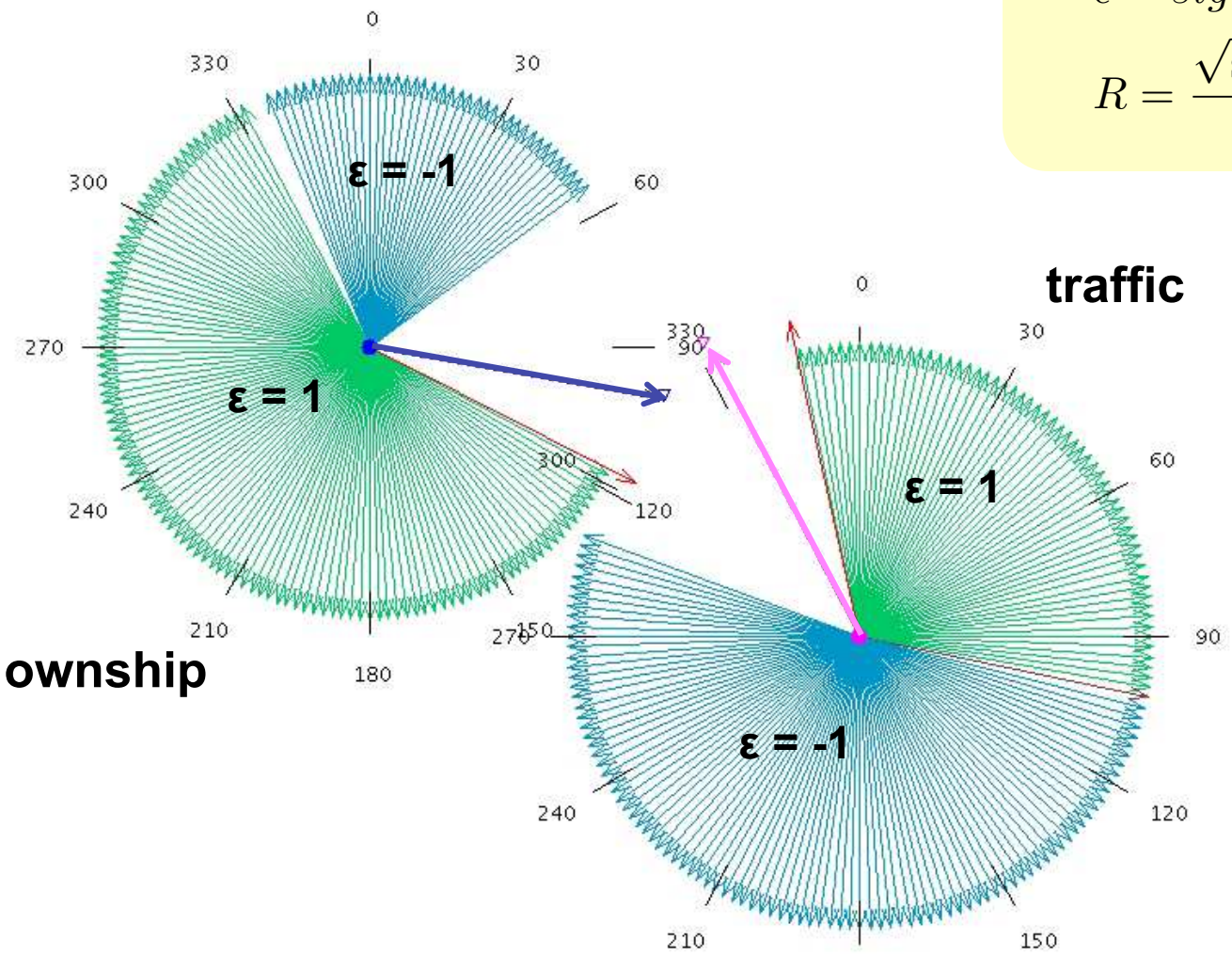
Horizontal Criterion

$$(\mathbf{s} \cdot \mathbf{v}) \geq \epsilon R(\mathbf{s}^{\perp} \cdot \mathbf{v})$$

where,

$$\epsilon = sign(\mathbf{s}^{\perp} \cdot \mathbf{v})$$

$$R = \frac{\sqrt{\mathbf{s}^2 - D^2}}{D}$$



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Summary

- Multiple algorithms and one criteria solves practical problems
  - Specialized algorithms for different aircraft performance envelopes
  - Algorithms can evolve
    - » don't have to upgrade the fleet at one time
  - Different algorithms from different vendors
    - » Different avionics suppliers
    - » Customize algorithms for different airlines
    - » International vendors
  - No costly NxN verification
- All coordinated solutions are really proposing a criteria
  - Complexity of criteria: "use my algorithm" vs. equations